Obscuring Material around Seyfert Nuclei with Starbursts

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ABSTRACT

The structure of obscuring matter in the environment of active galactic nuclei with associated nuclear starbursts is investigated using 3-D hydrodynamical simulations. Simple analytical estimates suggest that the obscuring matter with energy feedback from supernovae has a torus-like structure with a radius of several tens of parsecs and a scale height of ~ 10 pc. These estimates are confirmed by the fully non-linear numerical simulations, in which the multi-phase inhomogeneous interstellar matter and its interaction with the supernovae are consistently followed. The globally stable, torus-like structure is highly inhomogeneous and turbulent. To achieve the high column densities ($\gtrsim 10^{24}$ cm^{-2}) as suggested by observations of some Seyfert 2 galaxies with nuclear starbursts, the viewing angle should be larger than about 70° from the pole-on for a $10^8 M_\odot$ massive black hole. Due to the inhomogeneous internal structure of the torus, the observed column density is sensitive to the line-of-sight, and it fluctuates by a factor of order ~ 100. The covering fraction for $N > 10^{23}$ cm^{-2} is about 0.4. The average accretion rate toward $R < 1$ pc is $\sim 0.4 M_\odot$ yr^{-1}, which is boosted to twice that in the model without the energy feedback.

Subject headings: ISM: structure, kinematics and dynamics — galaxies: nuclei, starburst — method: numerical

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1. INTRODUCTION

Optically thick obscuring molecular tori have been postulated to explain various properties of active galactic nuclei (AGN), especially the two major categories of the AGN, namely type 1 and type 2. However, the true structure and the formation and maintenance mechanism of the torus have not yet been understood either theoretically or observationally.

Recently a number of observations have suggested a new aspect of Seyfert 2 galaxies (Sy2). It is pointed that there are possibly two types of Sy2s: one is a classic Sy2, an obscured Seyfert 1 nucleus. The other type II is a Sy2 with a nuclear starburst (Cid Fernandes & Terlevich 1995; Granato, Danese, & Franceschini 1997; González Delgado, Heckman, & Leitherer 2001; Levenson, Weaver, & Heckman 2001). In the latter case it is believed that a nuclear starburst is associated with the obscuring material whose scale is $R < 100$ pc. These observations imply that the classic picture of the unified model for AGNs, in which the diversity of the Seyfert galaxies is explained only by the geometrical effect of a geometrically and optically thick torus, may not be applicable to some fraction of the Sy2s (see also Maiolino et al. (1995)). More generally we propose here that there is an additional parameter in the unified models, namely, the strength of the nuclear starburst. It is this nuclear starburst and the mass of the black hole (BH) that determines the geometry of the obscuring torus.

While discussing the X-ray background, Fabian et al. (1998) proposed that low-luminosity AGN could be obscured by nuclear starbursts within the inner ~ 100 pc. They suggested that supernovae (SNe) from a nuclear starburst can provide the energy to boost the scale height of circumnuclear clouds and so obscure the nucleus. For simplicity, they assumed that the material sits in an isothermal sphere, and the gravitational effects of the central BH are ignored. This idea seems to be consistent with the recent observations of Sy2s with nuclear starbursts, Here we investigate the model in more detail. The problem is actually very complicated. We need to solve the 3-D inhomogeneous structure and dynamics of the ISM in the combined gravitational potential of the central massive BH, the central stellar system and the central massive gas distribution. We must handle the radiative cooling not only for the hot gas, but also for the cold gas, and include the feedback interaction between SNe and the inhomogeneous ISM. Numerical simulations are powerful tools for this kind of complicated problem.

Recently we presented high-resolution, 3-D hydrodynamical modeling of the ISM in the central hundred pc region in galaxies, taking into account self-gravity of the gas, radiative cooling, and energy feedback from SNe (Wada & Norman 2001; Wada 2001) (hereafter WN01 and W01). In this *Letter*, we apply this numerical method to the gas dynamics around the central massive BH, and study the starburst-AGN connection in Seyfert galaxies.

2. GEOMETRY OF OBSCURING MATERIAL AROUND THE CENTRAL ENGINE

In this section, we discuss the possible structure of the obscuring material around the central massive BH under the influence of the SN explosions detonating in the central massive gas cloud. The obscuring material will be inhomogeneous, and multi-phase and the geometrical thickness is assumed to be supported by its internal turbulent motion caused by energy input from SNe.

We assume the turbulent energy dissipation in a disk around the central massive BH is in equilibrium with the energy input from SNe. In a unit time and volume, the energy balance is

$$\frac{\rho_g v_t^2}{\tau_d} = \eta s_\star E_s = \eta\alpha\frac{v_c}{r}\rho_g E_s, \tag{1}$$

where v_t is turbulent velocity of the gas, τ_d is the dissipational time scale of the turbulence, E_s is the total energy injected by a SN, η is a heating efficiency per unit mass that represents how much energy from SNe is converted to kinetic energy of the ISM, and $s_\star$ is star formation rate per unit volume and time. We can assume the star formation rate is proportional to the dynamical time scale in the disk namely $s_\star \sim \alpha\Omega_c\Sigma_g h^{-1} = \alpha v_c/r\rho_g$, where v_c is the circular velocity, r is a radius, h is the scale height of the disk, Σ_g is surface density, and α is a constant ($\alpha \sim 0.02$ is suggested for a global star formation in spiral galaxies rate by Kennicutt 1998). The dissipational time scale τ_d can be simply assumed as $\tau_d = \xi h/v_t$, where ξ is a constant of order unity. Therefore eq.(1) is

$$\frac{v_t^3}{\xi h} = \eta\alpha\frac{v_c}{r}E_s. \tag{2}$$

Assuming hydrostatic equilibrium for the vertical direction of the disk, i.e. $\rho_g v_t^2 \sim \rho_g g h$, we have $v_t^2 \sim GM_{\rm BH}r^{-3}h^2$, for the case that the central massive BH dominates the gravitational potential (regime I), or $v_t^2 \sim \pi G\Sigma_\star h$, if the stellar disk or bulge potential dominates the potential. Here $\Sigma_\star$ is surface mass density of the stellar system (regime II). For the regime I, $h/r \sim v_t/v_c$ and for the regime II, $h/r \sim v_t^2/v_c^2$. Therefore from eq.(2), we have $h \sim (\xi\eta\alpha E_s)^{1/2} r v_c^{-1}$, for the regime I, or for the regime II, $h \sim (\xi\eta\alpha E_s)^2 r v_c^{-4}$. Using $v_{c,I} = (GM_{\rm BH}/r)^{1/2}$ for the regime I ($r < r_0$), or $v_{c,II} = (\pi G\Sigma_\star)^{1/2} r^{1/2}$ for the regime II ($r > r_0$), the disk scale height in each regime is

$$h_I(r) = (\xi\eta\alpha E_s)^{1/2} G^{-1/2} M_{\rm BH}^{-1/2} r^{3/2},\ r < r_0 \tag{3}$$

and

$$h_{II}(r) = (\xi\eta\alpha E_s)^2 (\pi G\Sigma_\star)^{-2} r^{-1}, \qquad r \ge r_0 \tag{4}$$

where r_0 is determined from $v_{c,I}(r_0) = v_{c,II}(r_0)$, and it is $r_0 = (M_{\rm BH}/\pi\Sigma_\star)^{1/2} \sim 56\,{\rm pc}\ \ M_8^{1/2}\Sigma_{\star,4}^{-1/2}$, where the BH mass, $M_8 \equiv 10^8 M_\odot$ and $\Sigma_{\star,4} = \Sigma_\star/10^4 M_\odot {\rm pc}^{-2}$. Therefore the maximum scale height at each regime is

$$\begin{aligned} h_{0,I}(r_0) &= (\xi\eta\alpha E_s)^{1/2} G^{-1/2} M_{\rm BH}^{1/4} (\pi\Sigma_\star)^{-3/4} \\ &\sim 22\,{\rm pc}\ \ (\xi_1\alpha_2\eta_{-3}E_{51})^{1/2} M_8^{1/4} (\pi\Sigma_{\star,4})^{-3/4}\,, \qquad (5) \\ h_{0,II}(r_0) &= (\xi\eta\alpha E_s)^2 G^{-2} M_{\rm BH}^{-1/2} (\pi\Sigma_\star)^{-3/2} \\ &\sim 1\,{\rm pc}\ (\xi_1\alpha_2\eta_{-3}E_{51})^2 M_8^{-1/2} \Sigma_{\star,4}^{-3/2}\,, \qquad (6) \end{aligned}$$

where $\xi_1 \equiv \xi/1.0$, $\alpha_2 \equiv \alpha/0.02$, $\eta_{-3} = 10^{-3} M_\odot^{-1}$, the total gas mass $M_{g,8} = M_g/10^8 M_\odot$. The scale height can be also expressed as $h_{0,I}(r_0) \sim 35\,{\rm pc}\ \ SFR_1^{1/2} r_6^{3/2} (\xi_1 E_{51}/M_{g,8})^{1/2}$, with the star formation rate $SFR_1 \equiv 1 M_\odot\ {\rm yr}^{-1}$ and $r_6 = r/60$ pc. Here we assume the Salpeter's IMF. Note that $h_{0,II} > h_{0,I}$, if $\alpha_2 \gtrsim 0.08$ for $\xi_1, \eta_{-3}, M_8, \Sigma_{\star,4}$, and E_{51}. Eqns (3) and (4) show that the disk has a torus-like structure (it looks more like a *concave lens* rather than a *bagel*), and its opening angle Φ is $\tan\Phi \sim r_0/h_{0,I} \propto (\xi\eta\alpha E_s)^{-1/2} M_{\rm BH}^{1/4}$, for $h_{0,II} < h_{0,I}$. Therefore $\Phi \sim 70^\circ$ for $\xi_1, \eta_{-3}, \alpha_2, M_8$, and $\Sigma_{\star,4}$. For the case that nuclear starburst is very active, e.g. $SFR_1 = 10$ and 100, we have smaller opening angles, i.e. $\Phi \sim 50^\circ$ and 20°, respectively.

If the star formation originates *via* gravitational instability in the gaseous disk, stars are not formed near the massive black hole. Assuming the Toomre's stability criterion $\Sigma_{crit} = \Omega_c c_s/\pi G = c_s G^{-1/2} M_{\rm BH}^{1/2} r^{-3/2}/\pi$, where c_s is the sound velocity, the critical radius r_c for which the disk with a uniform surface density is unstable is $r_c \sim \left[c_s^2 r_0^4 M_{\rm BH}/(M_g^2 G)\right]^{1/3}$, then $r_c \sim 3\,{\rm pc}\ \ c_1^{2/3} r_6^{4/3} M_8^{1/3} M_{g,8}^{-2/3}$, where $c_1 = c_s/(1\ {\rm km\ s^{-1}})$. The disk scale height for the stable disk would be very thin inside $r = r_c$, otherwise its shape would be represented by eqns (3) and (4). Therefore the gas around the central massive black hole with the nuclear starburst naturally forms a geometrically thick obscuring structure around the AGN, depending on the mass of the black hole, the gas mass, and the strength of the burst.

For the case of $h_{0,I} \gg h_{0,II}$, the average column density toward the nucleus as a function of the viewing angle ϕ ($\phi = 0$ is pole-on), $\tilde{N}(\phi) \sim \langle\rho_g\rangle L(\phi)$, where $L(\phi)$ is the path length in the torus, is approximately $\tilde{N}(\phi) \sim 5\times10^{24}{\rm cm}^{-2}\ \ M_{g,8} r_6^{-1} h_{22}^{-1} \Gamma(\phi)$, where $h_{22} \equiv h/22$ pc. $\Gamma(\phi)$ is a function that determines the path length in the torus, $\Gamma(\phi) \sim (1 - 2\tan^{-1}\phi)^{1/2}/\sin\phi$, for $r_0/h_{0,I} \lesssim \tan\phi \lesssim r_0/h_{0,II}$, or $\Gamma(\phi) \sim \cos^{-1}\phi$, for $\tan\phi > r_0/h_{0,II}$. $\Gamma \sim 0.8$ for $\phi \sim 80^\circ$. If the star formation rate is ten times larger and $h_{0,I} < h_{0,II}$, $\tilde{N}(\phi)$ is smaller by a factor of two.

3. NUMERICAL MODELING OF THE OBSCURING GAS IN THE GALACTIC CENTER

The argument in §2 is basically an order-of-magnitude estimate, and, consequently, detailed structure and evolution of the ISM in the galactic center should be verified by a fully non-linear, time-dependent numerical simulations. The star-forming massive gas should be an inhomogeneous with a velocity field that is turbulent (see WN01 and W01). SN explosions in such inhomogeneous system cannot be simply parameterized. The evolution of the SNe remnants will not be spherically symmetric, and should not be expressed by a simple analytic solution. As a result, it is not straightforward to estimate how much energy of a SN explosion is converted to the kinetic energy of the inhomogeneous, non-stational ISM. The energy dissipation rate as a function of time and position in the non-stationary turbulent gas disk needs to be explicitly calculated. In this section, we use a state-of-the-art numerical technique to clarify the evolution and structure of the gas in the star-forming region around the central massive BH.

3.1. Numerical Method and Model

The numerical methods are the same as those described in WN01 and W01. Here we briefly summarize them. We solve the same equations as eqns.(1)–(4) in W01 numerically in 3-D to simulate the evolution of a rotating ISM in a fixed gravitational potential. Here the external potential force in the momentum conservation equation (eqn. (2) in W01) is $\nabla\Phi_{\rm ext} + \nabla\Phi_{\rm BH}$, where the time-independent external potential is $\Phi_{\rm ext} \equiv -(27/4)^{1/2} v_c^2/(r^2 + a^2)^{1/2}$ with the core radius $a = 10$ pc and the maximum rotational velocity $v_c = 100$ km s^{-1}. The central BH potential is $\Phi_{\rm BH} \equiv -GM_{\rm BH}/(r^2 + b^2)^{1/2}$ with $b = 1$ pc. We also assume a cooling function $\Lambda(T_g)$ ($20 < T_g < 10^8$K) with Solar metallicity and a heating due to photoelectric heating, $\Gamma_{\rm UV}$ and due to energy feedback from SNe, $\Gamma_{\rm SN}$. We assume a uniform UV radiation field, which is ten times larger than the local UV field. The hydrodynamic part of the basic equations is solved by AUSM (Advection Upstream Splitting Method)(Liou & Steffen 1993). We use $256^2 \times 128$ Cartesian grid points covering a $64^2 \times 32$ pc^3 region around the galactic center (the spatial resolution is 0.25 pc). The Poission equation is solved using the FFT and the convolution method. The initial condition is an axisymmetric and rotationally supported thin disk with a uniform density profile (thickness is 2.5 pc) and a total gas mass of $M_g = 5 \times 10^7 M_\odot$ Random density and temperature fluctuations, which are less than 1 % of the unperturbed values, are added to the initial disk.

SN explosions are assumed to occur at random positions in the region of $|x|, |y| < 51$ pc and $|z| < 4$ pc. The average SN rate is ~ 1 yr^{-1}, which is corresponds to $\alpha \sim 0.3$ at $r = 20$

pc. The energy of 10^{51} ergs is instantaneously injected into a single cell as thermal energy. The 3D evolution of blast waves caused by SNe in an inhomogeneous and non-stationary medium with global rotation is followed explicitly, taking into account the radiative cooling. Therefore the evolution of the SNRs, e.g. the duration and structure of the SNe, depends on the gas density distribution around the SN.

3.2. Numerical Results

Figure 1 (a), (b) and (c) show volume-rendering representations of the density distribution of the gas around the massive BH in a quasi-stable state ($t = 1.6$ Myr) from three different viewing angles. In Fig. 1(a), the nuclear region can be seen, whereas the nucleus is obscured in Fig. 1(b) and 1(c). The right half of the Fig 1 (b) is a cross-section of the thick disk, and the inner structure of the thick disk is clear; the scale height of the disk is smaller in the central region than in the outer region as expected in §2, and the density structure is very inhomogeneous. The three panels in Fig. 1 together show that the gases around the central massive BH form a torus-like structure. The inhomogeneous, filamentary structure is quasi-stable. That is, the local inhomogeneous structure is time-dependent, but the global torus-like morphology does not significantly change during several rotational period.

In Fig. 2, we plot line-of-sight column density of the gas as a function of the viewing angle (90° is edge-on). The column density is higher in edge-on view. To achieve $N > 10^{23-24}$ cm^{-2}, which is suggested in observations of Sy2s with nuclear starbursts (Levenson, Weaver, & Heckman 2001), the viewing angle should be larger than $\sim 70°$ in this model. It should be noted, however, that the column density has large (about two orders of magnitude) fluctuations for the same viewing angle. This is caused by the inhomogeneous internal structure of the torus, which shows a Log-Normal distribution function (see W01). A factor of 100 change in the average column density corresponds to about $\pm 20°$ in the viewing angle. We find that a fraction of the solid angle, for which the nucleus is obscured, is 0.21, 0.37, 0.46, and 0.55 for $N > 10^{24}, 10^{23}$, 10^{22}, and 10^{21} cm^{-2}, respectively. These numbers are a factor 2–3 smaller to explain the ratio of Sy2s to Sy1s, which is about 4 (Maiolino & Rieke 1995), based on the 'strict' unified model.

From eqns. (5), we can expect the scale height of the disk of for $\alpha = 0.3$ is $h \sim 16$ pc at $r = 20$ pc and $h \sim 6$ pc at at $r = 10$ pc. This consistent with the numerical result. The column density predicted in §2 for $\phi \sim 80°$ fit the simulation. However, Fig.2 shows that the column density depends more strongly on the viewing angle than the analytical prediction. This is because the average density distribution for a z-direction in the torus is not constant, contrary to the assumption in §2.

Fig. 3 shows the time evolution of the gas mass inside $r = 1$ pc for the models with and without energy feedback. The average accretion rate is $\dot{M}_g \sim 0.4 M_\odot$ yr^{-1}, which is roughly twice that in the model without feedback. The turbulent viscous time scale in this system is $t_{\rm tub} \sim r^2/\nu_{\rm tub}$ with viscous coefficient $\nu_{\rm tub}$. Using $\nu_{\rm tub} \sim v_t \times l_t$, where l_t is the largest eddy size which is about the scale height of the disk (~ 10 pc), the turbulent viscous time scale is $t_{\rm tub} \sim 10^8 (v_t/10 {\rm km\,s^{-1}})^{-1}$ yr. This is the same order of the numerical result, i.e. $M_g/\dot{M}_g \sim 5 \times 10^7 M_\odot / 0.4 M_\odot {\rm yr}^{-1}$.

4. DISCUSSION

The estimate in §2 suggested that the opening angle positively correlates with $M_{\rm BH}$. As $M_{\rm BH}$ increases, the critical radius for the gravitational instability is also larger. This implies that low luminosity (i.e. small $M_{\rm BH}$) AGNs are obscured for larger fraction of the viewing angle than the high luminosity AGN, if, quite reasonably, the mass accretion rate has a positive dependence on the mass of the central engine. In other words, luminous type 2 objects, such as type 2 quasars are less frequently observed in the optical than type 1 quasars. They could be observed mainly X-rays, and this is consistent with observations (Norman et al. 2001; Lehmann et al. 2001; Akiyama et al. 2000).

Krolik & Begelman (1988) (KB) claimed that stirring by stellar processes is never strong enough to compete with energy dissipation in the clumpy torus. One should note, however, that in their order of magnitude estimate, a much smaller, thicker torus (~ 1 pc) is assumed than in our extended disk model. Therefore KB need large velocity dispersions (> 200 km s^{-1}) to keep the disk thick, because thick disks with $h/r \sim 1$ require $v_t/v_c \sim 1$. The velocity dispersion for $h/r \sim 1$ can be less than 50 km s^{-1} for $r \gtrsim 30$ pc. The smaller velocity dispersion is favorable, because the energy dissipation rate is smaller (see eq.(2)). KB also pointed out that a luminosity-to-gas-mass ratio, L/M_g, for the stellar stirring model would be a factor 100 larger than the observed values. This is also not the case for a 100 pc scale obscuring material. For the analytical model presented here, $L/M_g \sim r^{-3/2}$. In fact, a much larger molecular gas mass is expected on such a scale (e.g. Kohno et al. (1999)). Recent IR and X-ray observations of Seyfert nuclei (e.g. Granato, Danese, & Franceschini (1997)), on the other hand, suggest a 100 pc scale extended obscuring material. This picture is consistent with our model of the extended starburst supported obscuring region in which case we still obtain a geometrically thick disk with velocity dispersions $\lesssim 50$ km s^{-1}. Note also Pier & Krolik (1992) and Ohsuga & Umemura (2001) for the effects of radiation pressure on supporting the obscuring torus.

The present model suggests that the ratio of Sy2s to Sy1s cannot be explained only by

the orientation of the viewer relative to the torus. In Sy1s, the star formation rate in the nuclear region would be smaller than in Sy2s. The strict unified model, in this sense, should be modified by including the strength of the nuclear starburst.

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Fig. 1.— 3-D density distribution represented by a volume-rendering technique. The colors represent the relative opacity based on the line-of-sight column density, but it does not represent the absolute opacity or any physical value. The regions colored red or yellow are more optically thick than the blue regions. The right half of (b) is a surface section.

Fig. 2.— Column density vs. viewing angle. The column density toward the nucleus is calculated for the density distribution of a model shown in Fig. 1 every $\theta \sim 4^\circ$ and 4° for azumithal direction.

Fig. 3.— Time evolution of the gas mass inside $R < 1$ pc for two models (with and without energy feedback). The solid line represents the mass accretion rate $0.3 M_\odot$ yr^{-1}.

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